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Radiation Degradation Modeling of High-Efficiency GaAs/Ge Solar Cells

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The performance modeling and predictions of the radiation degradation of solar cells is extremely important in designing a power system that will satisfy spacecraft requirements for an entire mission duration. High-efficiency GaAs/Ge solar cells are more efficient and more resistant to space-particle radiation than conventional Si solar cells, but a complete physical performance degradation model has not been developed that accurately predicts the GaAs/Ge solar-cell radiation degradation characteristics. The conventional minority-carrier diffusion length degradation model used to predict the performance of silicon solar cells does not accurately predict the observed GaAs/Ge solar cell performance degradation. A detailed radiation degradation modeling analysis examines why the conventional model does not accurately predict the performance degradation of GaAs/Ge solar cells and offers suggestions for a more accurate radiation degradation model.

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Introduction

The radiation degradation of solar cells and solar arrays is extremely important to spacecraft power system designers since often the satellite mission duration is determined by the space-particle radiation degradation of the power system components. Since solar cells (solar arrays) are the most common power source component in satellite power systems, their performance and radiation degradation characteristics are critical in proper power system sizing and operations. GaAs/Ge solar cells are more efficient and have shown superior resistance to the space-particle radiation environment than silicon solar cells,[1] and their use is becoming more common in satellite programs. However, since the advanced GaAs/Ge technology has not had a long heritage of space flight data, ground test measurements and theoretical performance modeling are extremely important. There have been many papers written on both the measured radiation degradation of GaAs/Ge solar cells[2,3,4,5] and the modeling of the solar cell performance,[6,7] but there still lacks a complete assessment of the accuracy of the models and the underlying solar cell physics. This report addresses application of the standard silicon solar cell degradation model to high-efficiency GaAs/Ge solar cells.

Radiation Degradation Data

The radiation degradation of GaAs/Ge solar cells has been previously investigated, and the performance data has been measured as a function of 1-MeV electron fluence.[2,3,4,5] Early GaAs solar cells were grown by liquid-phase epitaxy (LPE) and had only moderate efficiencies. Improved efficiencies were obtained by MOCVD growth of the GaAs layers, and due to cost and weight limitations, Ge was used as the bulk substrate material. Since the initial production of MOCVD GaAs/Ge solar cells, improvements in the beginning-of-life (BOL) efficiencies and increased yields have been obtained. However, while the BOL efficiencies have increased, the end-of-life (EOL) efficiencies (assumed to be 1×10^{16} 1-MeV electrons/cm^2) have remained relatively constant. Therefore, the normalized power ratios, irradiated maximum power/pre-irradiated maximum power, have actually decreased.[8]

Since the last reported radiation degradation characteristics of 1990 vintage GaAs/Ge solar cells, further improvements in the BOL efficiencies have been made, as well as improvements in narrowing the spread in efficiencies (standard deviation) in a production lot. It is anticipated that control of the factors that have increased the average efficiency and decreased the standard deviation will also result in a higher average EOL efficiency. An investigation into these assumptions is underway by examining the electron and proton radiation degradation of high-efficiency (minimum of 19.5% AMO) 1994 GaAs/Ge solar cells.

Standard Solar-Cell Degradation Modeling

The standard solar-cell radiation degradation model was developed from the reciprocal lifetime contributions caused by various sets of recombination centers and the basic relationship between minority carrier lifetime and diffusion length. The model involves degrading the minority-carrier diffusion length as a function of 1-MeV electron irradiation by a constant degradation factor. Specifically, the minority carrier diffusion length may be calculated by the following equation.

$$\frac{1}{L_{n,p}^2} = \frac{1}{L_{n0,p0}^2} + K_L \Phi, \tag{1}$$

where $L_{n,p}$ is the degraded electron or hole (respectively) minority-carrier diffusion length, $L_{n0,p0}$ is the pre-irradiation electron or hole (respectively) minority-carrier diffusion length, K_L is the minority carrier diffusion length degradation factor, and F is the accumulated 1-MeV electron fluence.

This type of modeling works well for Si solar cells where the emitter is formed by a very shallow diffusion into a large base material. Because the performance of the solar cell is dominated by the absorption, generation, collection, and recombination properties of the base layer, the solar cell may be modeled by only degrading the base minority-carrier diffusion length. Figure 1 shows the normalized maximum power, open-circuit voltage, and short-circuit current of a conventional K4-3/4 silicon solar cell (10 W-cm, BSR, DAR, 8 mil) as a function of 1-MeV electron irradiation.[9] The pre-irradiation solar cell performance was modeled using the commercial PC-1D program with the following material parameters: L_{n0} = 117.0 mm, S_n = 1E7 cm/s, S_p = 1E3 cm/s, $N_A = 1.34 \times 10^{15}$ cm^{-3}, $N_D = 2 \times 1020$ cm^{-3}, and t_e= 150 nm. The modeled performance degradation was calculated using $K_L = 1.174 \times 10^{-10}$ to reduce L_n while keeping the other material parameter inputs to PC-1D constant. Figure 1 shows that the degradation model predicts the solar cell performance to within 1% (maximum error occurs in open-circuit voltage at F = 1 × 10^{16} 1-MeV electrons/cm^2). The graph shows that the simple minority-carrier diffusion length degradation model may be used to accurately predict the open-circuit voltage, short-circuit current, and maximum power for a conventional Si solar cell at all levels of 1-MeV electron irradiation up to 10^{16} electrons/cm^2. Similar modeling results have been obtained for other high-efficiency Si solar cell designs where the solar cell performance is dominated by a single-layer (base) minority-carrier diffusion length.

GaAs/Ge Solar-Cell Degradation Modeling

To begin the radiation degradation modeling of GaAs/Ge solar cells, it is first important to accurately model the beginning-of-life (pre-irradiation) performance. Figure 2 shows a schematic diagram of a standard ManTech GaAs/Ge solar cell and the material parameters used in the PC-1D modeling program. The performance comparisons show that the PC-1D model accurately predicts the pre-irradiation GaAs/Ge solar cell measurements.

Several groups have investigated the minority-carrier diffusion length degradation constant (K_L) for GaAs, and the literature reports values in the range of 2.5×10^{-7} to 2.5×10^{-8}.[10] Figure 3 shows how the minority-carrier diffusion lengths in the emitter, base, and AlGaAs window layer are degraded using the K_L equation with $K_L = 2.5 \times 10^{-7}$ and $K_L = 2.5 \times 10^{-8}$. Evident from Figure 3 is that regardless of the pre-irradiation minority-carrier diffusion length (emitter diffusion length is greater than the base diffusion length), at high levels of 1-MeV electron irradiation, the diffusion length is determined by $(K_L F)^{-2}$. This is very important when modeling the end-of-life performance of GaAs/Ge solar cells. It also provides insight into why there is a narrower distribution in solar-cell efficiency at end-of-life versus beginning-of-life. The end-of-life performance is independent of the initial minority-carrier diffusion lengths (although the shape of the performance degradation, or rate of performance degradation, is dependent on the initial minority-carrier diffusion lengths).

Because both the emitter and base layers of the GaAs/Ge solar cell are active in absorbing photons and generating electron-hole pairs, each layer must be analyzed separately. The effects of independently varying the minority-carrier diffusion length of each layer on the ManTech GaAs/Ge solar cell performance is calculated using the PC-1D program while keeping the other material parameters constant. The minority-carrier diffusion lengths are varied by changing the minority carrier lifetimes ($L = \sqrt{D\tau}$) of each layer from 100 ns to 0.01 ns. This range allows the solar cell performance to be modeled for both improvements and degradation of the minority-carrier lifetimes (diffusion lengths). Figure 4 shows the maximum power of the ManTech GaAs/Ge solar cell as a function of minority-carrier diffusion length for each layer. As expected, the minority-carrier diffusion length in the window layer does not affect the solar cell performance to a large extent. However, the emitter minority-carrier diffusion length shows a dominating effect on the solar cell performance and is significantly more limiting than the base minority-carrier diffusion length. This is a significant result and is caused by the inability of the generated carriers in the emitter to reach the depletion region and be collected. Also, the graph shows that a 5% increase in solar cell performance may be gained by increasing the base minority-carrier diffusion length. Increasing either the emitter or window layer minority-carrier diffusion length does not greatly affect the solar cell performance. Again this is anticipated, as once the emitter minority-carrier diffusion length is sufficiently long for the generated carriers to reach the depletion region, performance gains are not expected.

Once the minority-carrier diffusion length effects on solar cell performance and the K_L-radiation effects on the minority carrier diffusion length are known, it is then possible to model the radiation degradation of GaAs/Ge solar cell performance. Figure 5 shows the normalized performance

of three different degradation models and the measured performance of 1990 GaAs/Ge solar cells (labeled EQFLUX because the data was supplied with the EQFLUX program from JPL). Each of the three solar cell models uses a constant series resistance (R_s), shunt resistance (R_{sh}), and $n = 2$ recombination diode saturation current (I_{02}) as functions of irradiation throughout the calculations. At each fluence of 1-MeV electron irradiation, the minority-carrier diffusion lengths in the window, base, and emitter layers are calculated from the K_L equation and are supplied as inputs to the PC-1D program. Model A in Figure 5 uses the same K_L value for the window, base, and emitter layers ($K_L = 2.5 \times 10^{-7}$). Model B in Figure 5 also uses the same K_L value for the three layers but uses a different value ($K_L = 2.5 \times 10^{-8}$). Evident from Figure 5 is that neither model accurately predicts the measured solar cell performance. Model B predicts too little degradation in the open-circuit voltage, short-circuit current, and maximum power. Model A predicts significantly too much degradation in maximum power and short-circuit current but too little degradation in the open-circuit voltage. Therefore, it is evident that a model based on a single K_L value for all three solar-cell layers will not accurately predict the measured solar cell performance. Model C uses two different K_L values, one for the base and one for the emitter. Since the emitter minority-carrier diffusion length is the dominating factor in determining the end-of-life short circuit current and the K_L value determines the minority-carrier diffusion length at high levels of electron irradiation, the emitter layer K_L value was chosen to match the measured I_{sc} at 1×10^{16} 1-MeV electrons/cm^2. The base layer K_L value was chosen to match the measured V_{oc} at 1×10^{16} 1-MeV electrons/cm^2. However, at this level of electron irradiation, the predicted maximum power does not match the measured P_{max}, nor does the shape of the calculated short-circuit current and maximum power degradation curves. Therefore, even allowing for separate K_L values in both the emitter and base layers, the model does not accurately predict the measured GaAs/Ge solar cell performance degradation.

Since the simple model of degrading only the minority-carrier diffusion length in the emitter and base layers did not accurately predict the measured GaAs/Ge solar cell performance degradation, additional factors were investigated. The light-biased I-V curves as functions of 1-MeV electron irradiation for an average GaAs/Ge solar cell were curve-fit (using the least-squares method) to the double-diode equation to provide the four main solar-cell parameters: I_{01}, I_{02}, R_s, and R_{sh}. Figure 6 shows the series and shunt resistance as functions of 1-MeV electron irradiation. The graph shows that while there is an increase in series resistance and a decrease in shunt resistance, the values are well represented by their respective averages. Also, the changes in the resistance values do not greatly affect the solar cell performance. Figure 7 shows the depletion region recombination diode saturation current (I_{02}) as a function of 1-MeV electron irradiation and the I_{02} values calculated from the minority-carrier lifetimes[11] used in the PC-1D calculations in Model C above (the best-fit model that separately degrades the emitter and base minority-carrier diffusion lengths). The graphs show remarkable agreement except at low levels of electron irradiation where the I_{02} term does not significantly affect the solar cell performance (I-V curve fitting for I_{02} is least accurate in this range). Figure 8 shows both the curve-fit and calculated[12] solar-cell diode reverse saturation current (I_{01}) as a function of 1-MeV electron irradiation. Again, the calculated I_{01} is obtained using the solar-cell material properties from the most accurate model above (Model C).

At low levels of electron irradiation, the curve-fit and calculated values are in excellent agreement. However, at moderate and high levels of electron irradiation, the curve-fit I_{01} value is significantly

greater than the calculated value. This implies that some other material property in the I_{01} equation (i.e., surface recombination velocity, diffusion coefficient, etc.) is changing as a function electron irradiation in addition to the minority-carrier diffusion length. Therefore, a simple model that degrades only the minority-carrier diffusion length is not adequate to predict the radiation degradation of GaAs/Ge solar cells.

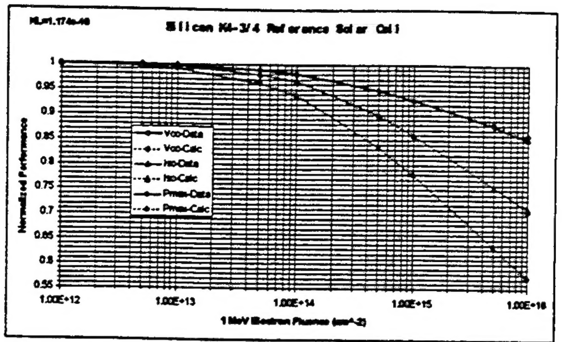

Figure 1. Modeled and Measured Silicon K4-3/4 Solar Cell Performance Radiation Degradation.

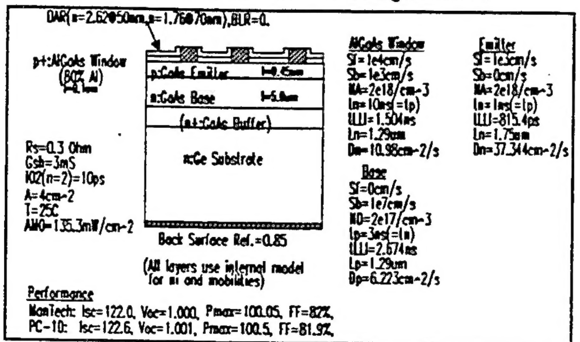

Figure 2. ManTech GaAs/Ge Solar Cell Design and PC-1D Solar Cell Modeling Material Inputs.

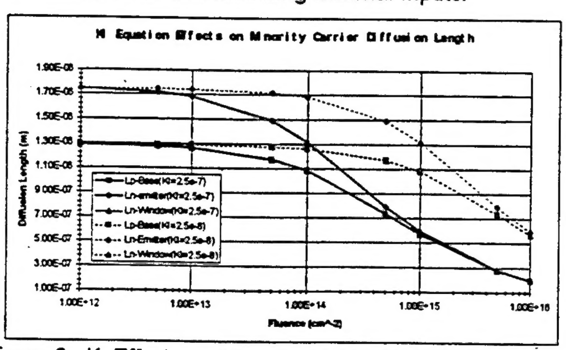

Figure 3. K_L Effects on Minority Carrier Diffusion Length.

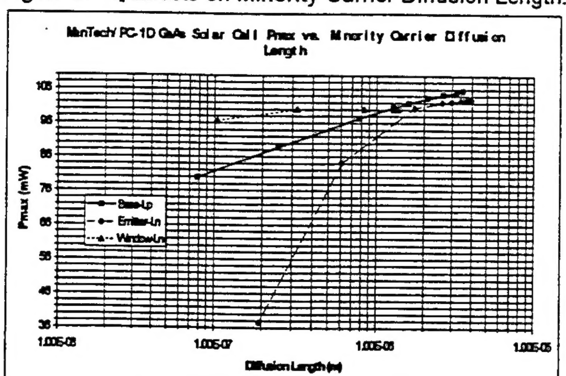

Figure 4. GaAs/Ge Solar Cell Performance as a Function of Minority Carrier Lifetime.

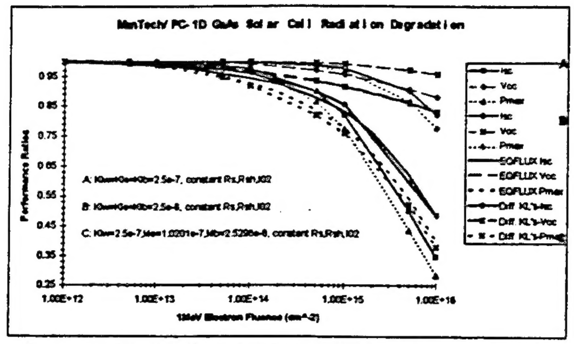

Figure 5. Modeled and Measured GaAs/Ge Solar Cell Performance Radiation Degradation.

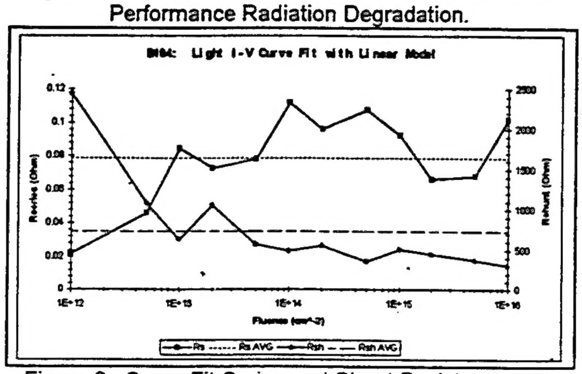

Figure 6. Curve-Fit Series and Shunt Resistances as Functions of Electron Irradiation.

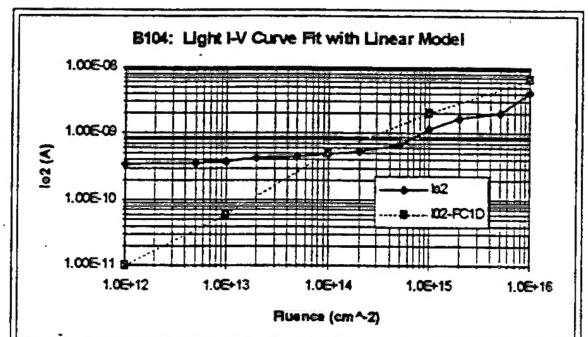

Figure 7. Curve-Fit and Calculated I_{o2} Values as Functions of Electron Irradiation.

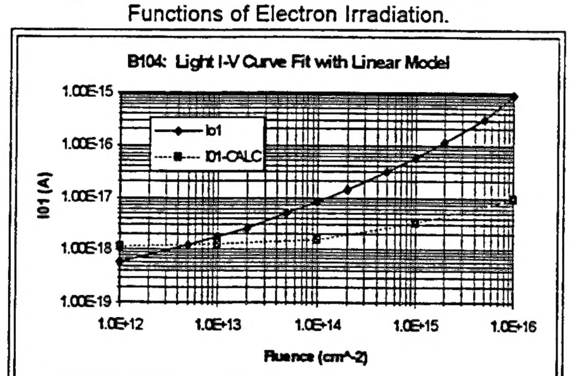

Figure 8. Curve-Fit and Calculated I_{o1} Values as Functions of Electron Irradiation.

Summary

The conventional model used to predict the performance degradation of silicon solar cells does not adequately predict the radiation degradation of GaAs/Ge solar cells. Analysis of the simple minority-carrier diffusion length degradation model and the measured solar cell performance reveals that the diffusion length is not the only solar-cell material parameter that is changing with radiation. A more detailed, comprehensive radiation degradation model is needed to accurately predict GaAs/Ge solar cell performance. However, it is also apparent that the emitter minority-carrier diffusion length is the performance-limiting factor in the radiation degradation of GaAs/Ge solar cells, and an increased end-of-life efficiency could be obtained by a thinner emitter layer.

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